-A Wetland Simulation Module for the MODFLOW Ground Water Model

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Abstract

The alteration of wetland habitats by natural and anthropogenic processes is an issue of worldwide concern. Understanding the changes that occur in wetlands often requires knowledge of how surface water levels relate to adjacent aquifer systems. The ability to simulate surface water movement and its interaction with ground water and wetland slough channels is a desirable step in the design of many projects constructed in or near wetlands. Currently, most ground water flow models incorporate wetland systems as general head boundary nodes. The purpose of this research was to develop a computer package for the widely used MODFLOW code that would simulate three-dimensional wetland flow hydroperiods and wetland interactions with aquifers and slough channels. The ground water flow model was used to reproduce the surface water flow process through wetlands, and then to estimate new flow rates and values using a Manning-type equation. This package represents flow routing, export and import of water, and evapotranspiration from wetlands for different hydroperiods. A basic verification procedure for the numerical solution of the diffusion equation was applied, based on a test case that was solved using a two-dimensional surface water model. This example is a transient solution to the diffusion equation, in which the initial conditions were depicted by a sinusoidal water surface profile and a flat bottom.

Introduction

Wetland habitats have been extensively altered over the years by commercial and residential development. As a result, some aquifers are literally dying due to habitat destruction, excessive drainage, flooding, or water quality degradation. Coastal wetlands are especially vulnerable, and are becoming polluted and disappearing at an alarming rate. In this study, the principal investigators have developed a carefully researched two-dimensional method, using the MODFLOW model, to measure the impacts of commercial, industrial, and residential development. By applying the method of pm-project analysis and planning, as outlined in this study, consideration can be given to wetlands, coastal regions, and aquifers during early stages of the development process. Changes can then be made to the project design to minimize water resource impacts.

Natural and anthropogenic processes alter wetland habitats. The ability to accurately simulate surface water movement in wetlands and slough channels, along with its interaction with ground water, is important for many projects. Currently, most ground water flow models incorporate wetland systems as general head boundary nodes (Merritt 1995), although wetlands can also be simulated as constant head nodes, or by using stream routing or lake stage packages. Most ground water and surface water flow models have been developed independently. Interaction between subsurface flow and surface flow in wetlands has not yet been simulated with an integrated model (Swain and Wexler 1993; Restrepo et al. 1992). Landscape models have been used to simulate wetland conditions; however, these models generally do not have a rigorous physical basis. Although reliable calibrations can be achieved by this type of model for carefully defined physical conditions, the reliability is questionable under varied physical conditions.

A previous model was implemented to simulate transient ground water flow in wetlands, using a rewetting procedure (Merritt 1995). The uppermost layer of the model represents wetland overland sheet flow as grid cells that have high equivalent hydraulic conductivity. This layer may become dry and need to be rewetted seasonally (Merritt 1995). The overall hydrologic budget or wetland overland flow were not considered in the model scheme, although the rewetting procedure made it possible to simulate the thickness of overland sheet flow, along with aquifer water table elevations.

The simulation of wetland hydrodynamics needs to give fundamental consideration to the physics of surface flow processes. Surface water flow in wetlands can be represented as sheet flow through dense vegetation, but overall water movement is often dominated by wetland slough channel flow, i.e., flow through a network of open water channels that exist between areas or patches of dense vegetation (Lewandowski 1993).

The wetland package described in this paper includes both of these surface flow components: sheet flow through dense vegetation and channel flow through a slough network. The wetland module package is incorporated into the MODFLOW ground water model code (McDonald and Harbaugh 1988) and enables the top layer of the grid system to contain overland flow and channel flow simulations. The wetland module can account for vegetation characteristics, simulation of surface flow routing, the export and import of water, and evapotranspiration. This extended model makes it possible to simulate the areal expansion and contraction of wetland systems and the associated water routing (horizontal and vertical) in response to different hydrologic conditions.

In this paper we describe the conceptual wetland model formulation, the mathematical formulation, and present a preliminary verification of the method. The verification procedure was based on comparison of the results predicted by the model with results obtained from a transient solution for the diffusion equation. The initial conditions consisted of a sinusoidal water surface profile and a flat bottom (Lal 1996a).

Conceptual Wetland Model Formulation

The wetland simulation model considers surface flow, wetting and drying, evapotranspiration (ET), and the vertical and horizontal flux components of the wetland-aquifer interaction. Sheet flow

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through dense vegetation and channel flow through a slough network (Lewandowski 1993) are conceptually represented by flow routing in large shallow water bodies that interact with slough channels.

Within densely vegetated wetland areas, surface water has low horizontal velocity and the flow generally follows the overall topographic gradient. Slough channels have less vegetation and the direction of flow follows the predominant slough orientation. The flow velocity in the slough channel is higher than the velocity of sheet flow.

Sheet flow through dense vegetation is simulated in a three-dimensional formulation. The MODFLOW ground water model is used to simulate uniform flow through dense vegetation. Instead of the Darcy equation (Freeze and Cherry 1979), a semiempirical Manning-type equation (Kadlec 1990) is used to represent surface water movement. This component is illustrated in Figure 1. Channel flow through a slough network is indirectly defined using the concept of the cell-by-cell anisotropy factor to create preferential flow orientations. In addition, the Kadlec equation (Kadlec 1990) is used to represent uniform surface water flow through the channel cells. This component is also illustrated in Figure 1.

The rate and direction of sheet flow through dense vegetation (Figure 2) are controlled by numerous factors, i.e., the topographical gradient, water depth, vegetation type, vegetation density, thickness of the soil substrate (generally muck, marl, or peat) layer, proximity of slough channels, precipitation, ET, and any other sources or sinks (Cowardin 1979). The sheet flow zone is a type of porous medium that, together with plant stems and soil, forms a layer which interacts with the underlying aquifer (Figure 2). The free water surface in the system may change from one level to another (e.g., from water level 1 to water level 2, as depicted in Figure 3a, due to normal variation in hydroperiods).

In the scenario where surface water levels drop to level 2, a portion of the underlying soil is exposed. The soil upper surface then becomes the top of the unconfined aquifer layer (Figure 3b). Wetting and drying of wetlands are part of the natural processes of these ecosystems (Lewandowski 1993). According to Mitsch and Gosselink (1993): "The hydroperiod is the seasonal pattern of the water level of a wetland and is like a hydrologic signature of each
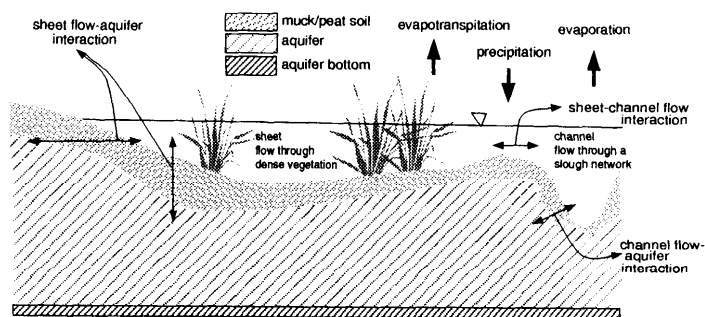

Figure 2. Vertical schematic of the surface water pathways in wetlands.

wetland type. It defines the rise and fall of a wetland's surface and subsurface water. It characterizes each type of wetland, and the constancy of its pattern from year to year ensures a reasonable stability for that wetland. The hydroperiod is an integration of all inflows and outflows of water, but it is also influenced by physical features of the terrain and by proximity to other bodies of water."

The soil layer underneath the water body can be simulated as part of the top layer (e.g., surface water body), as an independent confined/unconfined layer, or as part of the aquifer underneath. The model is able to effectively handle the drying and rewetting process when the appropriate option for the wetland simulation model is chosen. Because the horizontal and vertical flux components of the wetland-aquifer interaction are important, wetland and ground water flow cannot be simulated independently. Mathematically speaking, the surface water body in the wetland can be thought of as a continuation of the aquifer with a porosity close to 1.0. The model is designed to integrate surface and ground water flow using the horizontal and vertical interblock conductance. This wetland simulation module may be used to evaluate land-use impacts related to the export and import of water. Such impacts may include changes in the average water level in a single cell or group of cells, and in the total number of dry cells throughout the wetland areas.

The anisotropy factor in MODFLOW is defined for each layer as the ratio of hydraulic conductivity along a column to hydraulic conductivity along a row (McDonald and Harbaugh 1988). A modified block-centered flow package was developed to represent a cell-by-cell anisotropy factor. The interaction of slough channels with
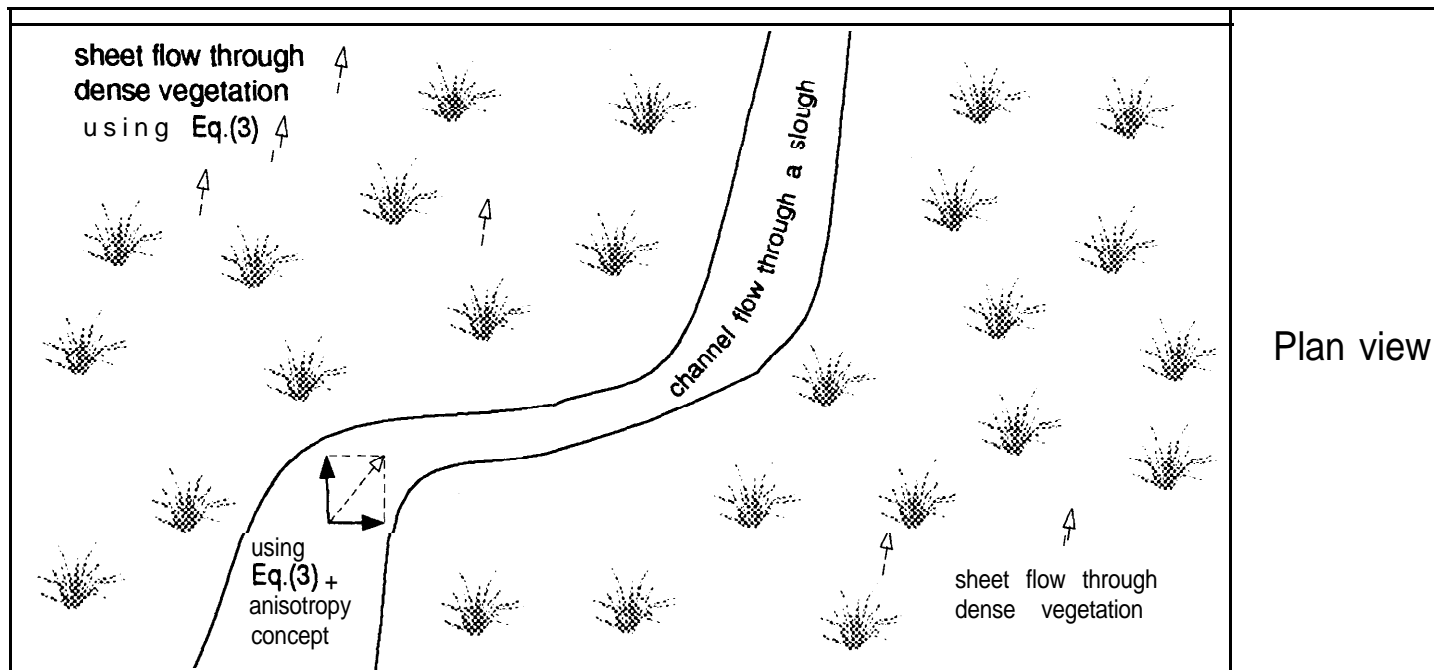

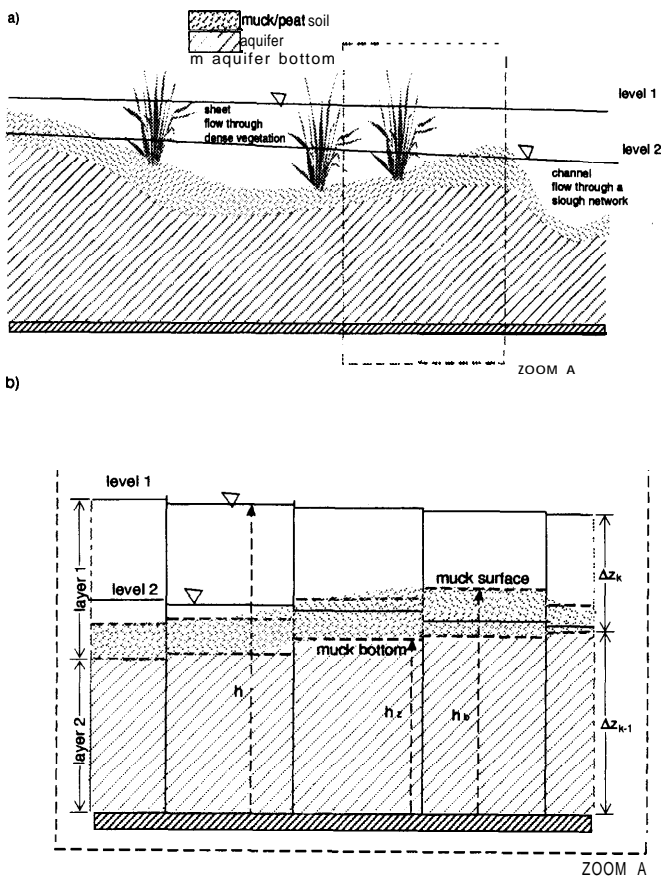Figure 1. Schematic of the main surface water flow components in wetlands.

Figure 3. (a) Vertical schematic of the surface water level fluctuations; (b) detail of discretization of the wetland system considering the soil as part of the top layer.

wetlands and the aquifer could thus be indirectly simulated. Changes to the block-centered flow package were made in such a way that the model is fully compatible with the original USGS model. Internally, each value of the anisotropy factor for each layer is propagated in each cell within the layer. Therefore, for the user of the regular **MODFLOW** model version, the changes are transparent. Water may be moved from one location to another within the system, or exported out of the model system, to represent the effects of artificial wetland management.

Mathematical Formulation

The mathematic basis of the various features that were considered in the wetland model, including sheet flow through dense vegetation, horizontal and vertical components of the sheet flow-aquifer interaction, channel flow through a slough network, evapo-transpiration, and water diversions, are described in the following sections.

Sheet Flow Through Dense Vegetation

Surface water flow is governed by the equations of continuity and momentum. A simplified overland flow equation is stated using the diffusive wave approximation. The diffusion equation is obtained by combining the continuity equation and the momentum equation and neglecting the acceleration terms. The resulting equation describes a gradually varied unsteady flow. The system of equations can be written in two dimensions along the principal directions of surface water flow (Singh 1996):

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = -\frac{\partial h}{\partial t} + (R - I - ET - W) \quad (1)$$

$$S_{fx} = \frac{\partial h}{\partial x} \qquad S_{fy} = \frac{\partial h}{\partial y} \quad (2)$$

where h [m] is the hydraulic head, S_{fx} and S_{fy} are friction slopes in the x and y directions, respectively, q_x [m²s⁻¹] and q_y are the components of the overland flux in the x and y directions, R [ms⁻¹] is rainfall rate, I [ms⁻¹] is infiltration rate, ET [ms⁻¹] is the evapo-transpiration rate, and W [ms⁻¹] represents any other sources or sinks of water.

The Kadlec (1990) equation for overland flow in a specific direction, can be expressed as:

$$q = K h^\beta S_f^\alpha \quad (3)$$

where α and β are coefficients of the hydraulic head, and K is the conductance coefficient of the equation. Kadlec (1990) states that if the Reynolds number is anticipated to be in the laminar range, it is reasonable to use a equal to 1 .O, and if it is in the turbulent range, a is equal to 0.5. The exponent β is a function of vegetation and water depth and ranges from 2.0 and 4.0 (Kadlec 1990). The conductance coefficient, K, is defined herein as the inverse of an equivalent roughness coefficient, n. The flow components per unit width, q_x and q_y can then be expressed as:

$$q_x = T_x \frac{\partial h}{\partial x} \qquad q_y = T_y \frac{\partial h}{\partial y} \quad (4)$$

where the transmissivity components in the x and y direction, T_x [m²s⁻¹], and T,, are expressed using Equations 2, 3, and 4 as:

$$T_x = \frac{1}{n_x S_{fx}^{(1-\alpha)}} (h - h_b)^\beta \qquad T_y = \frac{1}{n_y S_{fy}^{(1-\alpha)}} (h - h_b)^\beta \quad (5)$$

where h_b is the top surface elevation of soil above sea level as shown in Figure 3b. The differential equation of overland flow without sources or sinks is described as:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S_y \frac{\partial h}{\partial t} \quad (6)$$

where the specific yield S,, is considered to be close to 1.0 (McWhorter and Sunada 1977).

When the soil layer underneath the water body is simulated as part of the top layer, the equivalent transmissivity, T, can be calculated, adding the transmissivity of the underlying soil to the equivalent transmissivity of the surface water body areas. The value of the compound, T, in a specific horizontal direction can be expressed as a function of h:

$$T = \left[\frac{1}{nS_f^{(1-\alpha)}} (h - h_b)^\beta\right]_{\text{surf. water}} + \left[K_b(h_b - h_z)\right]_{\text{muck}} \text{ for } h_b < h \quad (7a)$$

$$T = \left[K_b (h - h_z)\right]_{\text{muck}} \quad \text{for } h_z \leq h \text{ s } h_b \quad (7b)$$
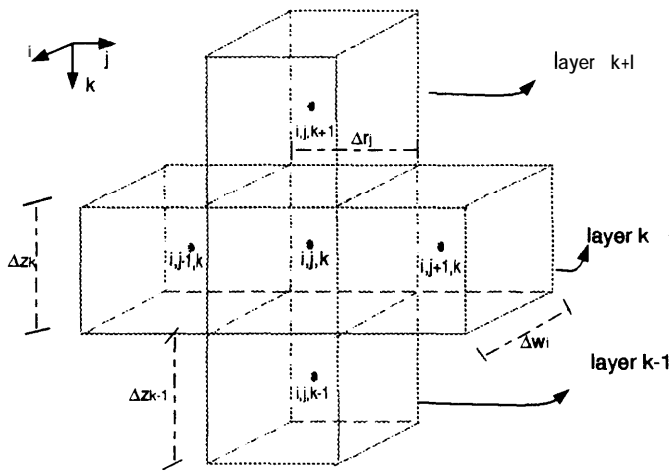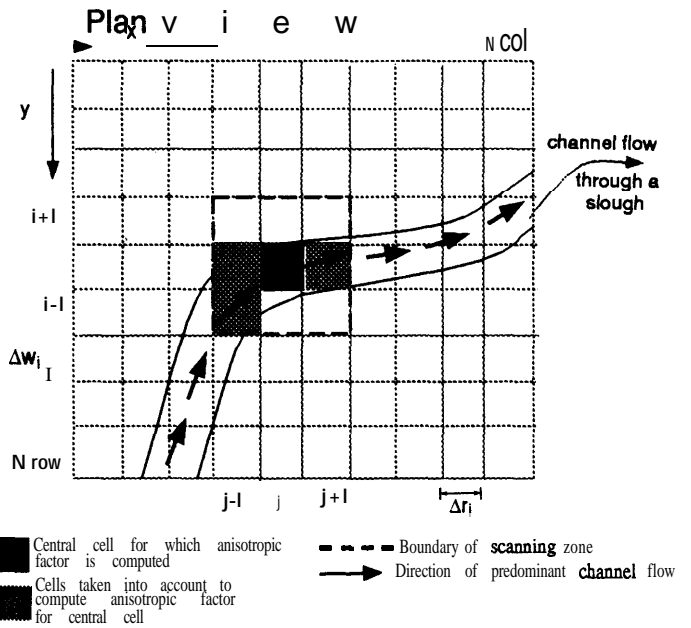
Figure 4. Definition of the cell dimensions along rows.

Figure 5. Slough cells (shadow cells) affecting the orientation of the flow in a center cell within the scanning zone.

where K_b is the hydraulic conductivity of the muck, and h_z is the bottom elevation of the soil above sea level. With this compound approach, the value of T may vary to represent any condition defined by Equations 7a, 7b, and 7c. When the model is applied to the case represented by Equation 7a, the effect of the value of soil transmissivity is insignificant relative to the corresponding value for the surface water. However, the soil layer plays an important role in the vertical direction, as is expected. When Equation 7b is used in the model, the soil characteristics control the flow in both the horizontal and vertical directions. It is assumed that the case represented by Equation 7c will only occur rarely and if it occurs, the wetland process would be terminated. When the substrate is represented by an independent, semiconfined layer, and the water level is below the top surface of the soil, the top layer becomes dry and the soil underneath the wetland becomes an unconfined layer (the soil layer changes from confined to unconfined). The existing MOD-FLOW rewetting package (McDonald et al. 1992) allows rewetting to occur within the top layer of the system.

Horizontal and Vertical Components of Sheet Flow-Aquifer Interaction

The model domain is discretized both horizontally and vertically as depicted in Figure 4. Based the principle of block-centered finite-difference methodology, a head value computed at the center of each cell is assumed to represent an average head value in each cell. The associated node properties, including the transmissivity, specific yield, and source terms in each square, are assumed to be the average of T, S,, and the integrated value of q over the cell, respectively. MODFLOW uses the four adjacent nodes around the cell i,j to formulate the finite-difference equation. For example, the interblock horizontal conductance of two half-cells in series, evaluated between ij-1 and i,j cells, can be expressed as:

$$\frac{1}{C_{i,j-1/2}} = \frac{1}{C_{i,j}} + \frac{1}{C_{i,j-1}}$$ (8)

$$C_{i,j} \cdot T_{i,j}^x \frac{\Delta w_i}{\Delta \frac{r_j}{2}} \qquad C_{i,j-1} = T_{i,j-1}^x \frac{\Lambda w_i}{\Delta \frac{r_{j-1}}{2}}$$ (9)

where $T_{i,j}^x$ and $T_{i,j-1}^x$ are the values of transmissivity evaluated in cells i,j and i,j-1 in the x direction, Δw_i is the grid dimension in the y direction, and Δr_j is the grid dimension in the x direction. The interblock

conductance between i-1,j and i,j cells in the y direction, $C_{i-1/2,j}$ is given as a function of the cell-by-cell anisotropy factor.

The wetland areas contribute water or receive water from the aquifer, depending on the head gradient between the wetland and the aquifer. The interactions of the wetland areas, in the vertical direction, with the aquifer are computed using a Darcy flow equation as follows:

$$Q_{i,j,k-1/2} = C_{i,j,k-1/2}(h_{i,j,k} - h_{i,j,k-1})$$ (10)

where $h_{i,j,k}$ is the surface water elevation, $h_{i,j,k-1}$ is the aquifer water level elevation, and $C_{i,j,k-1/2}$ is the equivalent interblock conductance $[m^2 s^{-1}]$. The interblock vertical conductance, evaluated between cells $i,j,k-1$ and i,j,k with the confining bed (soil), is computed as:

$$\frac{1}{C_{i,j,k-1/2}} = \left[\frac{1}{C_{i,j,k}}\right]_{water} + \left[\frac{1}{C_{i,j,k}}\right]_{muck} + \left[\frac{1}{C_{i,j,k-1}}\right]_{aquifer}$$ (11)

Since the vertical elevation of the surface of water that is moving through wetland areas exhibits negligible head losses, the wetland conductance is assumed to be much (from 100 to 1000 times) larger than the soil or aquifer conductance. The first term in the right-hand side of Equation 11 is thus negligible under most conditions. The soil or aquifer conductances are the main factors that control the vertical process and are given by the following equations:

(a) (soil) $\qquad C_{i,j,k} = A_{i,j,k} K_{ij,k}^x \frac{\Delta w_i \Delta r_j}{\frac{\Delta z_k}{2}}$

(12)

(b) (aquifer) $\quad C_{i,j,k-1} = A_{i,j,k-1} K_{i,j,k-1}^x \frac{\Delta w_i}{\frac{\Delta z_{k-1}}{2}}$

where Δz, is the thickness of the soil layer, $A_{i,j,k}$ is the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity for the soil layer in the x direction, $K_{i,j,k}$ is the horizontal hydraulic con-
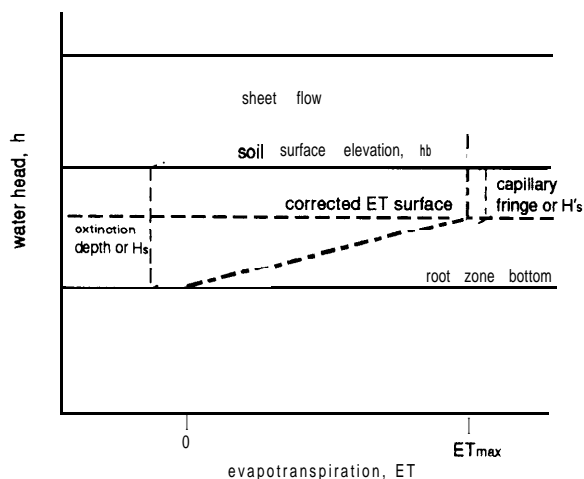
Figure 6. Evapotranspiration as a function of water head in wetlands.

ductivity for the soil cell, Δz_{k-1} is the thickness of the aquifer layer, $A_{i,j,k-1}$ is the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity for the aquifer layer in the x direction, and $Ki_{i,j,k-I}$ is the horizontal hydraulic conductivity for the aquifer cell.

Channel Flow Through a Slough Network

A slough channel can be divided into reaches, each of which represents a segment of the slough channel contained within a cell. A scanning zone is designated as a group of cells surrounding a given slough channel cell (i,j) that may affect the orientation of flow in that cell and are used to compute the preferential direction of flow in the cell (Figure 5). The size of the scanning zone should be defined to at least equal the maximum number of cells across the width of the slough at any point.

In Figure 5, the maximum number of cells within the width of the slough is equal to three cells for the sake of this discussion (i.e., the size of the scanning zone is three rows by three columns). By default, in the computer program, the minimum size for the scanning zone is 3 by 3. For example, the main orientation of the slough in cell i,j is obtained by weighting the possible orientation of the slough channel in the cell i,j. The shaded cells in Figure 5 are examined and the possible orientations for a slough cell are defined as a function of the grid dimensions. The average angle is computed using the weighted average of each orientation. After weighting the orientations, the anisotropy factor, which is tangent to the orientation, can be determined. The result is a conceptual representation of the channel flow. Since the finite-difference approach is used, ideally one axis of the grid system should match the main direction of the slough channel.

Evapotranspiration from Wetlands

Evaporation (ET) behaves differently in the two cases that are depicted in Figure 3 during wet and dry seasons. The wetland ET process usually does not depend on water levels under wet conditions and is essentially equal to the saturated ET rate. Under dry conditions, ET is more likely to depend on water levels (Restrepo et al. 1996). In this latter case, the MODFLOW assumptions apply (McDonald and Harbaugh 1988), with consideration given to correct for capillary effects. The ET rate, expressed in terms of wetland water levels as depicted in Figure 6, is:

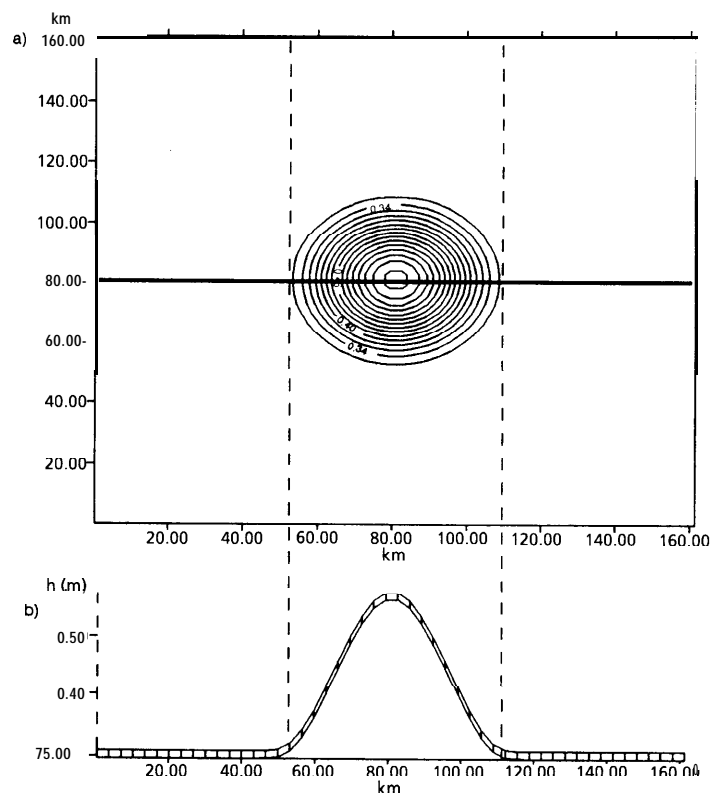$$ET = ET_{,,,} \qquad \text{for } h_b - H,' < h \qquad (13a)$$

Figure 7. Surface water level initial conditions for the model domain: (a) surface water level contours; (b) cross section along center row.

$$ET = 0 \qquad \text{for } h < h_b \quad H_s \qquad (13b)$$

$$ET = ET_{,,,} \frac{(h - h_b + H_s)}{(H_s \quad H_s')} \text{ for } h_b - H_s \leq h < h_b - H_s' \quad (13c)$$

where h_b is the soil surface elevation, h is the wetland head, H_s is the extinction depth, H,' is the depth of the soil capillary fringe, and $ET_{,,,}$ is the maximum ET rate.

Water Diversions

Man-made water diversions can have several impacts on wetlands. This portion of the program facilitates simulation of the effects of water injection/recharge and withdrawal in a region. For practical purposes, it is assumed that each water diversion comes from, and is discharged into, a single layer in a specified cell that is independent of heads in the wetlands or aquifer areas. The mass balance for water injected or withdrawn is given by:

$$Q, = - E_f Q_w \qquad (14)$$

where Q_i is injection water flow, E_f is the efficiency of the withdrawal well, and Q_w is the withdrawal water flow.

Simulation Options within the Wetland Module

The wetland module has five options to describe vertical discretization of the wetland system: (1) soil layer as a component of the top wetland layer; (2) soil layer as an independent, semiconfined layer; (3) soil layer as a component of the aquifer layer; (4) soil layer as a controlled confined leaky layer and represented only by the vertical conductance between layers; and (5) soil layer as a component of the top aquifer layer only as a controlled confined leaky layer.
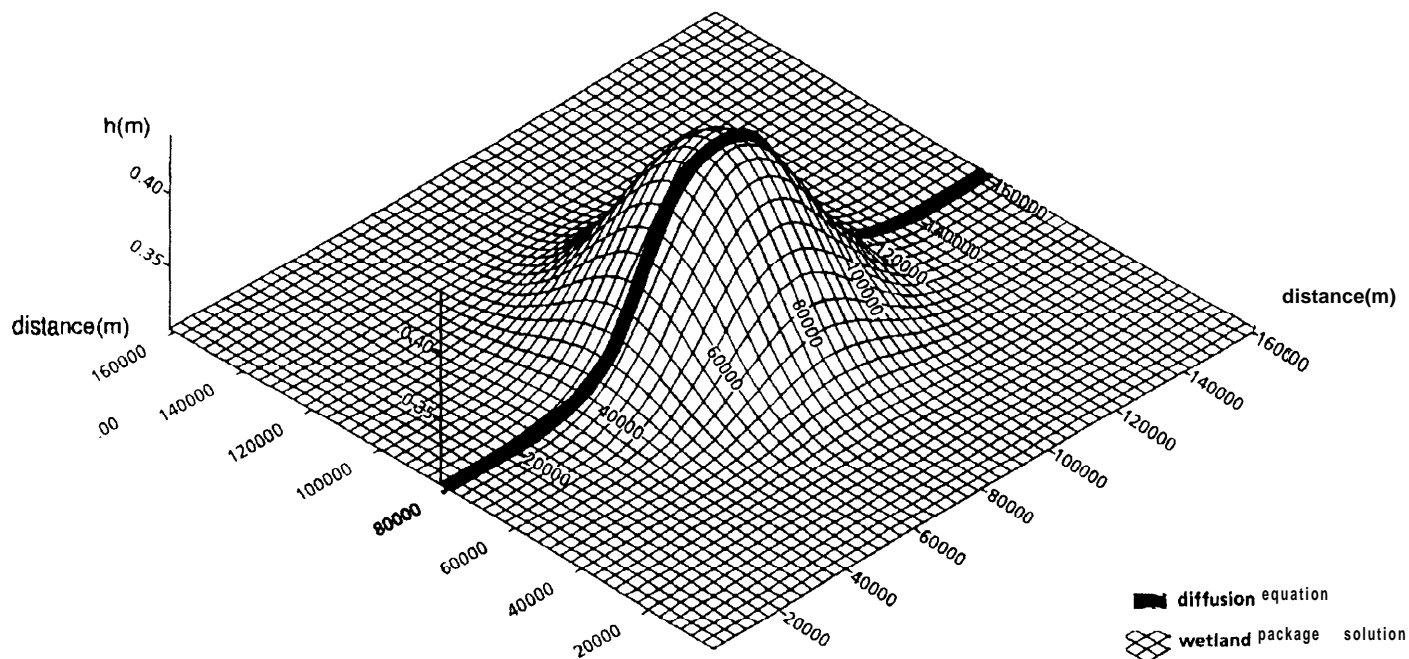
Figure 8. Potentiometric heads of the model domain after 12 days of simulation.

Data Required

The data requirements for the wetland model, which are needed to simulate surface flow in wetlands interacting with the aquifer, include the following: (1) coefficients α and β for the Kadlec equation (e.g., as derived using the Manning equation); (2) specific yield of the wetland water body; (3) roughness coefficient of the vegetation; (4) locations and dimensions of slough channel network cells; (5) hydraulic conductivity of the wetland soils; (6) specific yield of the soil layer; (7) elevation of the wetland soil top surface; and (8) depth of the soil capillary fringe. If water diversions are simulated. the following three additional data are required: (1) location of withdrawal or injection diversion cells; (2) rate of diversion or injection from or to the cell; and (3) ratio of the volume of water injected into the cell to the volume diverted (withdrawn) from the cell to account for water losses.

Basic Numerical Verification of the Diffusion Equation

To perform an initial verification of the wetland package, an ideal isolated wetland system (i.e., top layer only) was assumed to have an initial water profile represented by a bell-shaped mound of water and covered a total area of 162 km X 162 km (100 miles X 100 miles). The test case example has an axisymmetric solution, when the system has a sinusoidal water surface profile and a flat bottom as shown in Figure 7. The water level initial condition is represented as a series of concentric circles surrounding the highest point of the mound, which is the domain center. The initial water head h [m] at t = 0 is computed using the equation (Lal 1996a):

$$h = 0.4575 + 0.1525 \ \cos\frac{(\pi r)}{r_{max}} \qquad for \ \ r < r_{max} \quad (15a)$$

$$h = 0.305m \qquad for \ r \geq r_{max} \qquad (15b)$$

where r is the distance from the domain center, and r_{max} is 32,200 m. A constant boundary head of 0.305 m is maintained around the domain. The two-dimensional case is solved using a one-layer MODFLOW model with spatial resolutions of Ax = 1072.9 m in the

x direction and Ay = 1072.9 m in the y direction. The specific yield is defined as equal to 0.99 and evolution of the mound is simulated for a period of 12 days.

The numerical solution was verified using a weighted implicit finite volume method for overland flow that solves the two-dimensional diffusion flow equation (Lal 1996b). Iterative methods based on conjugate gradient method and preconditioners were used by Lal (1996b) to solve the sparse system of linear equations that resulted from the implicit solution method. The numerical solution that used the diffusion equation in the top layer matched closely with the numerical solution generated by Lal (1996b). One example is shown in Figure 8. The bold line is the solution of the one-dimensional diffusion equation and the mesh system is the solution generated by the wetland module in two dimensions.

Sensitivity Analyses

Intensive efforts were undertaken to verify the code, using hand calculation and computer spreadsheet methods, and to test the sensitivity of various model components for several test cases. Several values of the n and β parameters were used, and the results indicated that the overland flood wave propagates faster as the β coefficient increases. Therefore, for wetlands, a large conductivity for surface water is an important factor. In wetland systems, the surface water gradient is small; therefore, the exponent a is not very sensitive to changes and a value of 1.0 can be assumed. The changes in the hydraulic head due to changes the α parameter can also be achieved by adjusting the roughness coefficients. The value of specific yield for the sheet flow equation was assumed to be close to 1 .0. If the assumption can be made that the roughness coefficient is independent of the hydraulic head, then the roughness coefficient and specific yield are inversely proportional. Therefore, the changes in the hydraulic head that occur when the α parameter is modified can also be achieved by adjusting the specific yield. An important observation made from the results of the sensitivity analyses is that the selection of closure criteria is important for the accurate prediction of sheet flow levels. It was observed that the closure criteria had to be reduced as the β coefficient increased. Since the wet-

land gradient is small, the sensitivity due to nonlinearity was not an issue in this model. However, the number of iterations required to complete the analysis increased by a factor of between 5 and 10. The accuracy of the model results will also, to a large extent, be dependent on the size of the model cells, and the time interval used in the simulation.

Conclusions

The wetland package coupled with MODFLOW can be used to simulate three-dimensional sheet flow through dense vegetation and fluctuations of wetland water levels that may occur due to well-fields, ground water flow, channel flow through a slough network, water diversions, precipitation, and evaporation. The method for simultaneous solution of ground water and surface flow in wetlands incorporates an approximate diffusivewave routing equation into MODFLOW. This model has a variety of options which allow it to be applied in many different situations. It is particularly suitable for modeling sheet flow through dense vegetation and channel flow through a slough network. Within densely vegetated wetlands, the surface water flow component has a low horizontal velocity. Slough channels have less vegetation, higher surface water flow velocities, and flow generally follows the orientation of the channel. The influence of anisotropy can aid in the determination of the magnitude and direction of flow in the slough network. This model is also suitable for modeling the wetting and drying of the wetlands by combining vegetation and soils as part of the same layer. This approach allows the conservation equations to remain valid when the water surface falls below the soil surface.

A verification procedure was used to test the model code by using a hypothetical isolated wetland system. The initial water level conditions consisted of a bell-shaped mound of water. The numerical solution using the diffusion equation in the top layer of this model matched closely with the numerical solution generated by Lal (1996b). It has not yet been possible to test this model in a real-case scenario.

This simulation model can be used to determine the impacts of land-use changes. Such impacts may include changes in water levels and the number of dry cells in wetland areas. In order to be applied properly, the model should first be used to analyze a project in the pre-planning stage. Next, the project should be monitored throughout the construction phase. Finally, the model should be reapplied at the project conclusion to assess changes in the system. Monitoring and analyses should continue over a two- or three-year period in order to determine the full capabilities of the model to accurately simulate wetland processes and assess long-term effects.

Uses of this model, once such a comprehensive investigation has been completed, could be limitless. The goal of protecting wetlands against the effects of future commercial, residential, recreational, and industrial land development activities may be attainable. The primary limitation is the major effort needed to test this "wetland model" in a "real" field scenario. One significant

advantage of this model is that a two-dimensional approach provides a more practical basis to assess impacts on a per-acre basis. This study can also be easily designed to encompass an entire wetland as opposed to having to deal with isolated system elements. The investigators have recommended to the sponsoring agency that additional funding be provided to support study of a real-case scenario, including comprehensive monitoring and follow-up investigations.

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